

FINAL REPORT

SUMMARY OF HUMAN FACTORS IN SUPPORT OF SONAR SYSTEM DEVELOPMENT

prepared for

Engineering Psychology Programs
Psychological Sciences Division
Office of Naval Research

Contract N00014-68-C-0104
NR 196-078 8-18-67

BEST
AVAILABLE COPY

Applied Psychological Services

Science Center

Wayne, Pa.

Arthur I. Sigel
288

UNCLASSIFIED

Security Classification

AD 726 711

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Applied Psychological Services, Inc. Science Center Wayne, Pennsylvania 19087		2a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED	
		2b. GROUP	
3. REPORT TITLE Summary of Human Factors Work in Support of Sonar System Development			
4. DESCRIPTIVE NOTES (Type of report and inclusive dates) Final Report under Contract N00014-68-C-0104, 9/15/67 to 7/15/71			
5. AUTHOR(S) (First name, middle initial, last name) Arthur I. Siegel			
6. REPORT DATE July 1971		7a. TOTAL NO. OF PAGES 28 + ii	7b. NO. OF REFS 7
8a. CONTRACT OR GRANT NO. N00014-68-C-0104		9a. ORIGINATOR'S REPORT NUMBER(S) 7172-1	
b. PROJECT NO. NR 196-078/8-18-67		9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report) -	
10. DISTRIBUTION STATEMENT Approved for public release; distribution unlimited.			
11. SUPPLEMENTARY NOTES		12. SPONSORING MILITARY ACTIVITY Engineering Psychology Programs Psychological Sciences Division Office of Naval Research	
13. ABSTRACT A final report under Contract N00014-68-C-0104 is presented in two parts. The first part summarizes the sonar system oriented human factors work performed by Applied Psychological Services under the present contract. Part II contains an outline which can provide a basis for a sonar specific manual of human factors considerations in sonar system design, development, and test.			

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Security Classification

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Sonar Human Factors Engineering Psychology System Evaluation System Design Displays, visual Displays, auditory						

FINAL REPORT

**Summary of Human Factors in Support
of Sonar System Development**

Arthur I. Siegel, Principal Investigator

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ABSTRACT

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I. INTRODUCTION

This final report under Contract N00014-68-C-0104 contains two major parts. The first section summarizes the human factors efforts performed by Applied Psychological Services over a three-year period in order to extend the capability of new sonar systems. The human factors contributions included both experimental and analytical work and were concerned with such topics as task loads on operator and maintainer personnel, training requirements, design of displays and controls, work station organization, and evaluation of the effectiveness of the human/hardware interface.

The second part of this report is more general. It presents an outline of a manual relative to sonar system specific human factors considerations in sonar system design, development, and test. During the last five years, Applied Psychological Services (APS) has participated in the design and development phases of a number of surface and submarine sonar systems. This work has brought APS into contact with other laboratories specializing in sonar problems, into the literature of sound propagation and reception, and into certain original derivations, all focusing on the human role in sonar system operation and maintenance. The manual to be prepared will represent a sonar specific human factors compilation for the use of system, human factors, and mechanical design personnel involved in the development of advanced sonar systems.

PART I

Summary of Human Factors Work in Support of Sonar Systems
Performed under Contract N00014-68-C-0104

Introduction

This report section summarizes the human factors efforts engaged in over a three-year period under Contract N00014-68-C-0104 between Applied Psychological Services and the Office of Naval Research. The program was geared to extending the capability of advanced passive sonar systems and focused specifically on the AN/BQR-19 (TOPHAT) system. This sonar system extends the detection capability of SSBN submarines by providing information not provided by other onboard sonar equipment.

The major human interfaces in the TOPHAT system consist of a receiver cabinet and chart-type bearing time recorder (BTR) located in the sonar room, and at least one repeater display located in the ship's control center. The contributions of the human factors effort to this system's development included both experimental and analytical work, which concentrated on forecasting the loads imposed on the sonar technicians, on assisting toward the design of displays, controls, and workspace layouts, on predicting staffing and training requirements, on examining maintainability concepts in the system, and participating in system evaluations. The scope of these efforts is described in the paragraphs which follow.

Forecasting Technician Loads

Early in the development of any system, it is essential to obtain estimates of the probable load to be imposed on the human elements in the system. This load evaluation was especially necessary in the TOPHAT development because TOPHAT constituted an addition to the existing complement of onboard sonar equipment, i. e., its demands represented additional tasks to be superimposed on already extant tasks of the operator. To this end, the intellectual, visual, auditory, and control loads to be anticipated as the result of adding TOPHAT system operation to the current load of the operator was investigated by complementary methods. The first of these, intellectual load, was investigated by means of a method which is based on the formulations of Guilford and his associates (Guilford, 1967). Guilford, on the basis of an extensive set of factor analyses, derived a three-dimensional view of human intellectual functioning. The Guilford concept identifies 120 independent intellectual operations, contents, and products. From Guilford's 120, the 13 most relevant to sonar were submitted to sonar technicians for magnitude estimation of the extent to which they were necessary for the effective use of the TOPHAT equipment. The results indicated that the addition of TOPHAT would increase the intellectual load on the technician manning it by about 15 per cent each time it is used. Parenthetically, this technique for intellectual load analysis, first employed and developed by Applied Psychological Services under this ONR contract, has been recently utilized by two other organizations in the development of Naval systems.

Visual, auditory, and control loads were estimated through link analytic methods. To this end, experienced sonar technicians rated the frequency and importance of links between the TOPHAT operator and the other equipment and personnel in the sonar room. The results yielded a forecast of identical, and fairly high, visual and control loads by TOPHAT, along with a relatively low auditory load. Over all of the equipments with which the sonar operator is concerned, the visual load was indicated to be slightly higher than the control or the auditory load. Maximum load was indicated to be imposed by the AN/BQR-2 sonar set. The addition of TOPHAT was forecast to impose a considerable additional load on the sonar supervisor, although the increment was not believed to be sufficient to overload him to an undesirable degree. Accordingly, no change was recommended in the manning of the sonar room as the result of the addition of the TOPHAT system.

Design of Displays, Controls, and Workspace Layout

In order to assure that the TOPHAT system would meet human factors display, control, and workspace organization requirements, a Fleet interview program was initiated. The sample included officers and sonar technicians who currently man operational SSBN's. These interviews probed the transfer of information from equipment to operator(s), between operators, and from the operators to the equipments. The transfer of information was considered both within the sonar room and between the sonar room and the ship's control center.

The results of these interviews were coupled with experimental research and with the results of the operator load analyses, to yield recommended designs for the chart recorder display and controls, and for location of the system's components aboard various classes of submarines.

An experimental study of the ability of experienced SSBN officers to read and interpret the bearing time recorder in a variety of tactical situations was conducted. Among other variables, the use of an especially designed recorder paper was subjected to experimental test. The test results showed the suggested paper design to yield appreciably lower rates of display reading error. These results were reported to the Naval Ship Systems Command, and a recommended design for the BTR paper was presented on the basis of the study's results.

Interview and link and load results indicated a hierarchy of layouts and locations for the primary TOPHAT display and receiver cabinet. The tradeoff analyses on which the alternatives were based were presented, along with the recommended locations and layouts. The alternate locations suggested are presented in Figure 1.

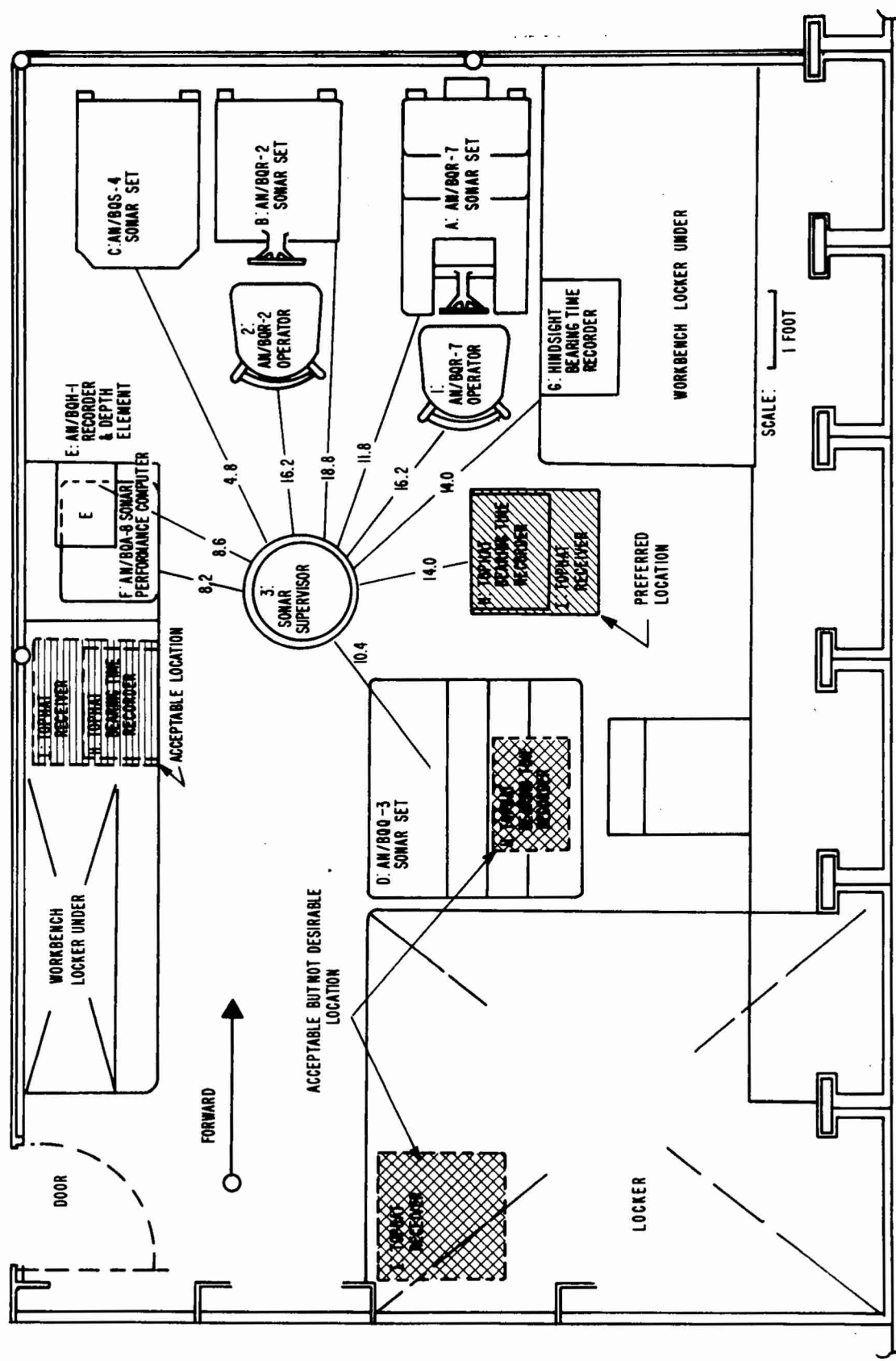


Figure 1. Suggested alternate locations for TOPHAT equipment (numbers shown are link values).

An additional important outcome of the fleet observation and interviews concerned integration of the remote TOPHAT recorder with other onboard displays in the ship's control center. The paper speeds of the chart recorders for the BQR-2, BQR-7, HINDSIGHT, and TOPHAT sonar systems are not the same. Bearing rate is inferred from trace angle on the chart, but this angle is in turn a function of chart speed. Thus, the impression was yielded of different bearing rates for the same target on a change of display mode.

The information transfer analysis and fleet interviews indicated the desirability of an auditory display in the ship's control center. For certain important tactical situations, the duty officer would be deprived of all input sources unless provided with an auditory presentation of TOPHAT information.

Finally, interview and experimental data indicated another modification to the design of the chart display. Initial design provided for a 60° overlap in the presentation of the TOPHAT coverage. This was found to constrict the display excessively and, accordingly, to increase the difficulty of the task of judging the bearing rate of displayed targets. On the basis of the research performed, reduction of the overlap to 30° was recommended.

These experimental and qualitative analyses also suggested a number of specific requirements for the location of the TOPHAT equipment items, for the design of its primary display and the presence of certain secondary displays (e.g., an auditory alerting indicator), and for the various manual controls in the system. In all cases, these requirements were reported to the Naval Ship Systems Command. In most of these cases, the tradeoff considerations were explicitly indicated.

In a somewhat separate study, an analysis of an alternate method for presenting topside information was developed. The alternate method was based on modifying the AN/BQR-2 system and would involve the addition of no new equipment to the sonar room. A preliminary analysis was presented to show the feasibility of the alternate system, and it was held that the alternate possesses at least the following advantages: (1) minimization of additional work load on sonar supervisor during periods when he is already quite busy, (2) a lack of a need to relocate any equipment or to add any equipment to the extant sonar room, (3) provision of an integrated display system for the AN/BQR-2 and the TOPHAT systems, the two systems which are primarily employed during ascent to periscope depth, (4) savings in the cost of acquisition because of the considerable use of existing equipment, (5) minimal increase in training requirements, (6) minimal maintainability degradation, because of the minimum addition of new hardware, and (7) maximum effectiveness because of the integrated system concept. The mechanical and the electrical design for this alternative concept was fully developed and presented.

Manning and Training Requirements

Manning and training requirements were derived through performance of task analyses of operations and maintenance actions and sequences, and integrating these results with the results of the previously performed link and load analyses. The detailed task analyses consisted of listing all of the subtasks included in the overall task, and identifying, for each, the relevant control-display relationships, perceptual-motor involvements, response criteria, and environmental conditions which might bear on operator performance. Equipment operation was analyzed separately by normal mode, auto alarm mode, and audio mode. Similarly, the maintenance task was analyzed separately by the major maintenance activities of operability testing, turnon and checkout procedures, fault isolation, and parts removal and replacement. Equipment operational tasks included were: testing recorder display, testing automatic alarm, audio listening, and obtaining figure of merit measurements. Fault isolation and removal and replacement tasks analyzed were both those performed on a scheduled basis and those performed only when some corrective action is indicated. The specific tasks of these type analyzed were isolation to and removal of NAFI modules or assemblies in the diagnostic assembly, a preamplifier in the preamplifier assembly, a faulty scan switch, slip ring, or delay line in the scan switch assembly, a component in the background noise circuitry, a component or NAFI-type module in the audio transformer circuitry, a component or NAFI-type module in the audio receiver, and a component or NAFI-type module in the audio meter channel.

The outcome of the task analyses in conjunction with the load and link analyses indicated that the current number of personnel required for standing a sonar watch need not change as a result of adding TOPHAT to the existing onboard sensing systems. For operations, no change was indicated to the manned positions or to the policy of utilizing other ratings as watchstanders for normal underway watches, so long as one rated sonar technician was present. Similarly, TOPHAT maintenance requirements were determined not to warrant any manning changes from current complements.

Training requirements derived from the analyses performed covered both operations and maintenance, and pointed to training objectives and the length, location, facilities, manuals, equipment, and specific content of the required training for the TOPHAT system. In general few new skills were found required for TOPHAT operations or maintenance. However, specific knowledge of use and employment of the system was identified for: (a) orientation of onboard SSBN technicians to TOPHAT, (b) orientation to TOPHAT of STS graduates of the Class A-1 Basic Sonar School, (c) inclusion in the Class C, General Submarine Sonar Technician, maintenance training course, and (d) familiarization training of officer personnel.

Human Factors in Maintenance

Maintainability, from the human factors point of view, was supported through a number of analyses. The manufacturer's designs and maintainability test plans were carefully analyzed to assure an optimum system from the point of view of maintainability. Specific recommendations were submitted concerning sampling considerations in regard to the choice of maintenance tests and demonstrations, clarification of the operational definition of mean time to restore, specification of permissible tools and job aids, and accessibility. Particular emphasis in this regard was placed on ease of recorder maintenance, stylus change, and paper replacement.

System Evaluations

The human factors tests to be performed during the Technical Evaluation (TECHEVAL) of the system were designed and specified in a test plan submitted to the Naval Ship Systems Command. The techniques utilized in the design of these tests were both qualitative and quantitative. The plan called for human factors personnel to observe operations of the three human interfaces with the system on a time sampling basis during the entire period of sea trials. Specified for particular attention during the observations were incidence of interference with other equipment, communications between stations, safety, display interpretability and transfer to other displays, maintenance provisions, and the ease of use of the TOPHAT controls.

Also designed into the technical evaluation plan was preparation and administration of a checklist of generally accepted human factors design criteria. These criteria covered such topics as anthropometry, environmental factors, communications, controls, displays, and maintainability. The plan specified a thorough checkoff form consisting of multiple items within each topic, and an evaluator administering this form during the sea trials.

Two sets of interviews were designed into the technical evaluation plan. One set was designed for conduct with ship control officers. It probed the use of the remote/repeater display and any problems associated with its location, operation, and interpretation. The other set of semistructured interviews was designed for conduct with enlisted sonar watchstanders. It covered the area of interequipment compatibility, effect of TOPHAT on communications and on sonar team interaction, ease of reading and use of the TOPHAT display, maintainability, setup, checkout, and test features, and any areas of specific deficiency indicated in the qualitative human factors observations.

The evaluation plan also specified two tests of the performance of the system. The first of these was directed to calibrating the detection range of the man equipment system, and utilized methodology adapted from the psychophysical method of limits. The detection range was treated as an absolute threshold, and a target ship was specified to execute a maneuver which brought it alternately closer and closer until well within range, then further and further away until well out of range, with three series of each. Sonar technicians were tasked with monitoring the equipment and reporting the presence or absence of the target every 30 seconds. The mean range (independently determined) over the six points of transition between presence and absence was specified as defining the detection threshold for each technician manning the equipment. The mean range over all technicians was called the detection threshold for the man equipment combination.

The second performance test in system evaluation specified a surface ship executing a 360° turn at 1° per second while the submerged TOPHAT submarine proceeded on a course describing a secant through the circle. At 30-second intervals, the technician monitoring the equipment was tasked with reporting target bearing, bearing rate, qualitative range, and qualitative change in range.

The data from the TECHEVAL were also analyzed through development of ROC curves, detection probability curves, range and azimuth reading accuracy curves, and confidence intervals, and the results were reported to the Naval Ship Systems Command.

In addition to these tests, during the entire development phase of the system, Applied Psychological Services hosted or participated in technical meetings and design review meetings, and critically evaluated all human factors documentation for the system.

LIST OF REPORTS UNDER CONTRACT N00014-68-C-0104

Letter Report: Chart design for TOPHAT BTR. Wayne, Pa.: Applied Psychological Services, June 1968.

Memorandum Report: Review and suggestions for action for an alerting signal for TOPHAT. Wayne, Pa.: Applied Psychological Services, April 1968.

Memorandum Report: Human factors technical evaluation plan for the AN/BQR-19 (TOPHAT) system. Wayne, Pa.: Applied Psychological Services, May 1969.

Memorandum Report: TOPHAT remote BTR display evaluation. Wayne, Pa.: Applied Psychological Services, June 1968.

Siegel, A. I., & Federman, P. J. Preliminary manning and training requirements for the TOPHAT (AN/BQR-19) system. (U) Wayne, Pa.: Applied Psychological Services, 1969. (Confidential)

Siegel, A. I., Fletcher, D. E., & Lanterman, R. S. Man-machine interface analysis for the TOPHAT system. (U) Wayne, Pa.: Applied Psychological Services, 1968. (Confidential)

PART II

Outline of a Manual of Sonar Specific Human Factors Considerations
in Sonar System Design, Development, and Test

Introduction

A body of sonar specific knowledge has developed during the years since World War II, and during the shorter time period since the launching of the first nuclear submarine. This has been a period of new developments in sonar technology, and of cementing the facts and operational experiences that had been previously acquired.

During the most recent five years, Applied Psychological Services has been a party to developments at the human interface of at least five new sonar systems. These developments have been published in technical reports, many classified, of Applied Psychological Services and of other military and industrial organizations active in this field. However, this information has never been brought together into a single, unified source. Moreover, due to the diversity of the sources, combing the literature is particularly difficult. Accordingly, the view was taken that a consolidation of human factors information in sonar systems is required. Further, it was believed that human factors methods and techniques, when divorced from the tactical context of their original use, could be presented in an unclassified document, and hence be made available to the profession in general. Part II of this report presents an outline for such a document. The outline does not attempt to recapitulate the general knowledge in the field of human factors--only to bring together the sonar specific information required for effective sonar system design. Similarly, the outline does not attempt to include material that is already included in current military standards and specifications. Again, only sonar specific information--not included in these sources--is involved.

Outline of a Manual of Sonar Specific Human Factors Considerations
in Sonar Systems Design, Development, and Test

I. INTRODUCTION

Why This Manual Was Prepared

- To augment MIL-STD-1472, MIL-H-46855, NAVWEPS OD 18413A (Vol. II) for sonar systems
- To assemble state-of-the-art information in design of submarine and surface sonar systems

Purpose of Manual

- Enunciate design principles
- Comprise criteria of acceptable design practices
- Comprise a basic reference document

For Whom Prepared

- Designer of sonar equipment and systems
- Agency monitoring technical design development

A Reader's Guide General Human Factors Reference List

Chapanis, A., Garner, W. R., & Morgan, C. T. Applied Experimental Psychology, Human Factors in Engineering Design. New York: Wiley, 1949.

Fogel, L. J. Biotechnology: Concepts and Applications. Englewood Cliffs, N. J.: Prentice-Hall, 1963.

McCormick, E. J. Human Factors Engineering. New York: McGraw-Hill, 1964.

McFarland, R. A. Human Factors in Air Transportation. New York: McGraw-Hill, 1953.

Meister, D., & Rabideau, G. F. Human Factors Evaluation in System Development. New York: Wiley, 1965.

Morgan, C. T., Cook, J. S., III, Chapanis, A., & Lund, M. W. Human Engineering Guide to Equipment Design. New York: McGraw-Hill, 1963.

Woodson, W. E., & Conover, D. W. Human Engineering Guide for Equipment Designers. Berkeley, Calif.: University of California Press, 1964.

II. THE SONAR MILIEU

Basis for Selection to ST Rating

- Basic Test Battery performance
- Auditory functioning
- Psychiatric factors

Major Contents of ST Training

- Characteristics of sound in water
- Principles and employment of passive listening
- Principles and employment of echo ranging
- Specific equipments
- Recognition and classification
- Sonar plots
- Maintenance
- Record keeping and administrative items

The Sonar Environment

Space Dimensions

- Drawings of Sonar Control Rooms and Sonar Equipment Rooms

Ambient Illumination

- White, 0.50 to 18.0 ft-candles
- Red, 0.06 to 0.4 ft-candles

Auditory Ambient

- Acoustic qualities of typical sonar control rooms
- Earphones
- Communications

III. HUMAN FACTORS IN SONAR EQUIPMENT

Information Presentations, General

- Relationship between accuracy of presentations and system sensing accuracy

Passive (listening) information

- Search, track in bearing, classification

Active (echo-ranging) information

- Search, track in range and bearing, aid to classification
- Ping-to-ping integration
- Doppler
- Frequency
- When mode used

Auditory Presentations

- Loudness
- Pitch, and change in pitch (doppler)
- Patterns and systematic changes re rhythm, timbre, pitch, strength
- Duration
- Dwell time
- Thresholding

Visual Displays

- Inclination/orientation of display for both seated operator and standing supervisor

Chart presentations

- Paper design
- Paper speeds
- Bearing scales
- Bearing rate information
- Trace width
- Trace separation
- Overlap
- Marking density
- Target alarm
- Illumination

Cathode Ray Tube presentations

- Formats
 - A-scan
 - B-scan
 - C-scan
 - D-scan
 - J-scan
 - Plan Position Indicator (PPI)
 - DIMUS-type
 - Difar-like
- Intensity levels
- Marking densities
- Number of echo-cycles (for active A-scan)
- Modulation by intensity, deflection (for active A-scan)
- Display size (primarily for PPI)
- Frame rate (for DIMUS-type)
- Own-ship and target ship(s) presentation
- Bearing scales
- Target bearing presentation
- Intensity coding vs. color coding (primarily for DIMUS-type)
- Display integration
- Classification displays

Standard Display Symbols

Control and Indicator Design

- Preferred control types
- BDI, S/N meter, etc., design
- Bearing rate devices
- Spoke suppression
- Attenuation
- Head sets and gain control
- Legending
- Grouping of functions
- Cursors and cursor control
- Time indications
- Special test features
- Malfunction indicators
- Degraded mode indicators
- Annunciator design
- "Alarm" indicators
- Filters
- Mode selection
- Illumination and its control
- Console lighting

Vigilance in Sonar

- Interindividual differences in detection performance on vigilance tasks
- Dual mode (auditory and visual) vigilance detection performance
 - dual mode, dual task performance--auditory vigilance detection in conjunction with visual tracking
- Vigilance detection and signal rate
- Vigilance detection and duration of watch period

Theory of Signal Detectability

Communications

Ancillary Equipment Functions

- Training
 - capability to utilize preprogramed auditory and visual material
 - . for on-the-job training
 - . for proficiency maintenance training
 - . for watchstander checkout
 - . for performance appraisal
- Recording

IV. HUMAN FACTORS IN SONAR SOFTWARE

Analytic Efforts During Conceptual State

- Operator and maintainer function analyses
 - use for design and training support
- Operational sequence analysis
 - use for design and training support
- Computer simulation
 - use for design and training support
- Experimentation
 - use for design and training support
- Display studies
 - Analytic Profile System
 - Display Evaluative Index

Task Analysis

- Operational Sequence Diagrams (OSD)
- Operator and maintainer workload analysis
 - intellectual load
 - perceptual load
 - motor load analysis

Training Requirements Derivation

- Multidimensional scaling analysis
- Computer simulation
- Reliability analysis for maintainer training requirements
- Use of other specified analytic methods

Manuals

- SIMM format
- "Explosion" diagrams
- Readability/comprehensibility analysis
 - Flesch technique
 - Cloze technique

V. HUMAN FACTORS IN SONAR MAINTENANCE

Dimensions of Sonar Equipment Spaces

- Surface ships
- Submarines

Typical Maintainable Sonar Equipment

- . Analog equipment
- . Digital equipment
- . NAFI modules

Typical On-board Test Equipment

Troubleshooting sonar equipment

- Automatic operations
- Semi-automatic operations
- Manual troubleshooting

Special problems in paper recorders

VI. HUMAN FACTORS IN SONAR SYSTEM EVALUATION

Static Human Factors Tests

- Safety inspection
- Compliance with applicable design specifications and standards
- Inspection for interference problems
 - physical interference
 - auditory interference
 - visual (line of sight) interference
- Sample checklists

Evaluation of Factory Training

- Expert review
 - content coverage
 - training method
- Utilization of principles of learning
 - transfer of learning
 - reinforcement
 - frequency of practice
 - whole task/part task treatment

Paper and pencil tests of knowledge

Performance tests

- Prepared scenarios/exercises
- Graduated difficulty levels
- Simulation
- Operations and maintenance

Trainee opinions

Evaluation of Manuals

- Readability/comprehensibility evaluation
 - Cloze technique
 - interviews

Technical Evaluation (TECHEVAL)

- Prepared exercises/scenarios
- Task frequency and importance considerations
- Simulation
- Check lists
- Operations and maintenance
- Technician opinion

Operational Evaluation (OPEVAL)

- Performance tests
 - prepared exercises/scenarios
 - frequency and importance considerations
 - random task sampling considerations
 - alerted and unalerted conditions
 - primary system equipment
 - ROC or FLOC curves
- Technician opinion

Maintainability Tests

Static considerations

- Clearances and accesses
- Test points, identification and access
- Safety factors
- Critical adjustment factors, tolerances
- Test target injection
- Special tools

Dynamic considerations

- Scheduled maintenance
 - down/off-line duration

Unscheduled maintenance

- Fault detection, troubleshooting, and system restoration
 - sampling of faults
 - random
 - frequency and importance
 - preprepared exercises/tests
 - time and accuracy recording

Repair

- Sampling of faults
- Common/interchangeable parts
- Electrical knowledge factors
- Mechanical knowledge factors
- Manipulative skill factors
- Critical time factors
- Preprepared exercises
- Performance evaluation
 - time
 - quality

Maintainer opinion

- Interview and written questionnaire
 - sonar technician, sonar supervisor, maintenance officer, division officer

VII. HUMAN FACTORS RELATED MILITARY STANDARDS

System design

Equipment design

- mechanical
 - . materials and finishes
 - . packing
 - . NAFI modules
- electrical

Maintenance

Reliability

Shipboard lighting

Shipboard noise (acoustics)

Abbreviations

Nomenclature

Training and training equipment

General human factors specifications and standards

- MIL-STD-1472, Human Engineering Design Criteria for Military Systems, Equipment and Facilities
- MIL-H-46855, Human Engineering Requirements for Military Systems, Equipment and Facilities
- NAVWEPS OD 18413A (Vol. II), Human Factors Design Standards for the Fleet Ballistic Missile Weapon System

VIII. THE HUMAN FACTORS ORGANIZATION

Relationship to program organizational structure

Staffing

Mode of operation

REFERENCE

Guilford, J. P. The nature of human intelligence. New York: McGraw-Hill, 1967.

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